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The transition between Makran subduction and the Zagros collision: recent advances in its structure and Active deformation

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Abstract

South-east Iran is the site of a rare case of young transition between subduction and collision. We synthesized recent results in geodesy, tectonics, seismology and magnetism to understand the structure and kinematics of the Zagros-Makran transition. Surface observations (tectonics, magnetism and geodesy) draw a transpressive discontinuity consisting of several faults striking obliquely to the convergent plate motion, whereas deeper observations (seismology) support a smooth transition across the fault system. No lithospheric transform fault has been created, even though the transition already behaves like a major boundary in terms of tectonic style, seismic structure, lithology and magnetism. The Zendan-Minab-Palami fault system consists of several faults that accommodate a transpressive tectonic regime. It is the surface expression of a southward propagation of the N-trending right-lateral strike-slip fault system of Jiroft-Sabzevaran. Within each system the numerous faults will coalesce into a single, lithospheric, wrench fault.

1 Introduction

Spatial transition between subduction and continental collision is by itself unstable and often a transform fault will develop to accommodate the differences in tectonic setting as the Chaman fault in central Asia does (Lawrence et al., 1992). Interestingly, the Hormoz strait area in Iran (26.5°N; 56.5°E, Figure 1) displays such a setting, but in a juvenile stage. At this point Arabia converges northward towards Eurasia at a velocity of 23-25 mm yr⁻¹ according to GPS measurements (Bayer et al., 2003; McClusky et al., 2003; Vernant et al., 2004; Bayer et al., 2006; Masson et al., 2007). The Arabian plate is oceanic to the east in the Oman Gulf whereas it is continental to the west in the Arabian platform (**Figure 1**). As expected, the

Arabian and Eurasian continental plates collide to the west, forming the NW-SE-striking Zagros fold-and-thrust belt (ZFTB), which is a continental accretionary prism within the Arabian plate and accommodates about 10 mm yr^{-1} of NNE-trending shortening (Alavi, 1994; Talebian and Jackson, 2002; Tatar et al., 2002; Blanc et al., 2003). To the east, Arabia subducts under Iran resulting in an extensive accretionary prism whose EW-striking Makran belt is the emerged portion (Byrne et al., 1992; McCall, 1997; Kopp et al., 2000). In-between, the structures in the Hormoz area define a curved structure connecting the Main Zagros Thrust (MZT) suture to the Makran frontal thrust (Figure 1); this curved structure probably represents the newly-formed transform fault. These structures connecting the Zagros and Makran mountain belts trend N-NNW, and are therefore very oblique to the N-S convergence velocity, with an expected transpressive character.

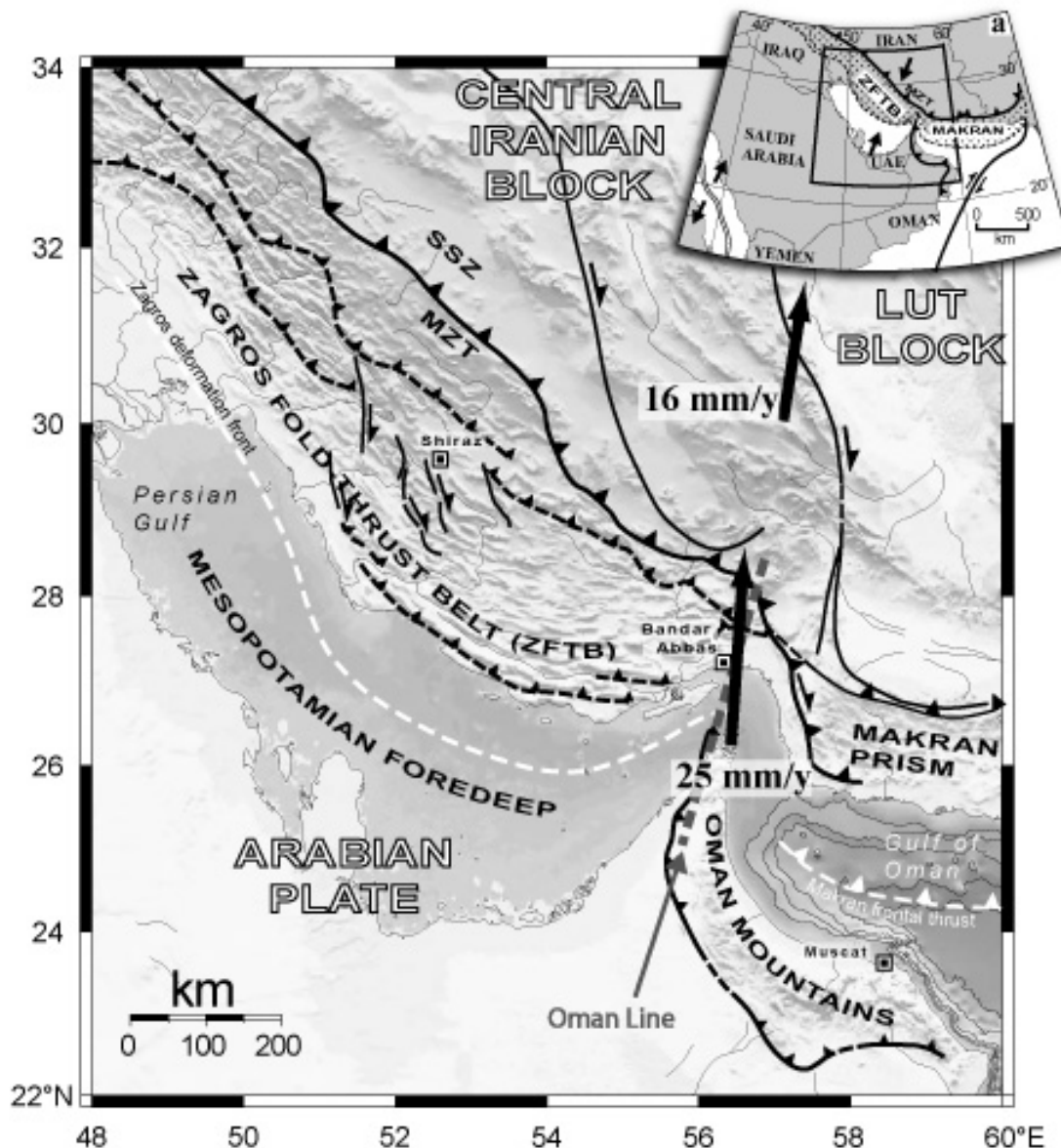


Figure 1. Map of South Iran/North Arabia (modified after Molinaro et al., 2005a). The arrows represent the velocity relative to Eurasia (Vernant et al., 2004). Note that the convergence accommodated through the Zagros Fold-and-Thrust Belt (ZFTB) is only $\sim 9 \text{ mm/y}$, and there is no value currently available for the part of the Arabia-Eurasia convergence accommodated through the Makran between Arabia and Lut (except using Vernant et al (2004)'s results with some hypotheses). MZT: Main Zagros Thrust; SSZ: Sanandaj Sirjan Zone.

This area has been studied for some times by geologists and geophysicists. The latter described a sharp boundary between the eastern and western domains called the ‘Oman Line’. Despite the associated low seismicity its sharpness was interpreted as evidence of a transform fault (Kadinsky-Cade and Barazangi, 1982).

In order to provide a better understanding of this newly-evolving transform fault system, the area has been recently studied with different geological and geophysical techniques in the framework of an Iranian-French collaboration including palaeomagnetism (Aubourg et al., 2004; Smith et al., 2005; Aubourg et al., 2008), tertiary and active tectonics (Molinaro et al., 2004; Regard et al., 2004; Molinaro et al., 2005a; Regard et al., 2005a), seismology (Yamini-Fard, 2003; 2007; in prep), and geodesy (Vernant et al., 2004; Bayer et al., 2006; Masson et al., 2007). The purpose of this paper is to provide a synthesis of these acquired data and to discuss this subduction-collision transition. Thus, after introducing the general setting of the area, the present-day and recent deformation and the upper crustal structure from balanced cross-sections, we discuss the deep crustal structure revealed by seismological studies and finally present the actual deformation rates from GPS/Geodesy.

2 Geological Setting

2.1 Zagros

The Zagros mountain belt is a NW-trending fold-and-thrust belt, consisting of a 6-15-km thick sedimentary pile which overlies Precambrian metamorphic basement (McCall et al., 1985; McCall, 1997). The sedimentary cover can be divided into three successive sequences. First, at its base, it is comprised of thick late Precambrian evaporitic deposits (the so-called ‘Hormoz Salt’) which constitute the main regional décollement for most of the larger folds within the Zagros fold-and-thrust belt (ZFTB). This layer is the origin of numerous salt diapirs that have pierced the overlying sedimentary cover and risen to the surface. A ~4000 m thick Cambrian to Eocene sequence forms the so-called Competent Group. Apart from the initial Cambrian-Carboniferous clastic formations, the majority of this group until Upper Cretaceous consists of massive platform carbonate rocks (James and Wynd, 1965; Faure-Muret and Choubert, 1971; Szabo and Kheradpir, 1978; Sharland et al., 2001). The remainder of the stratigraphic sequence is represented by the Miocene to Recent clastic sediments of the Incompetent Group. These molasse-type sediments, derived from the uplift and erosion of the Zagros Mountains, show a typical coarsening-up evolution from marine-to-continental clastics to coarse proximal conglomerates at the top (James and Wynd, 1965; Edgell, 1996; Hessami et al., 2001).

2.2 Makran

The Makran accretionary wedge stretches from Iran to central Pakistan and off the south coast of this area (Schluter et al., 2002). It has been formed by the subduction of the oceanic portion of the Arabian Plate beneath Eurasia and is built up by sediments scraped off the Arabian Plate since early Tertiary (Berberian and King, 1981; Harms et al., 1984; Kopp et al., 2000). Subduction was probably initiated during Palaeocene (Platt et al., 1988) and accretion started during Eocene times (Byrne et al., 1992). The modern Makran accretionary prism has developed since Late Miocene (Platt et al., 1985; Platt et al., 1988), and is still propagating seaward at a rate of $\sim 10 \text{ mm yr}^{-1}$ (White, 1982). Two features make this accretionary wedge unusual: (1) the sediment thickness on top of the oceanic crust is extremely high (at least 6 km); and (2) the dip angle of subduction is extremely low (~ 5 degrees, Jacob and Quittmeyer, 1979; Byrne et al., 1992; Carbon, 1996).

2.3 Transition Zagros-Makran

The Zagros and the Makran domains are both bounded to the north by a continuous ophiolitic belt along the Main Zagros reverse fault and its eastern continuation along the Makran Thrust (Figure 1) (McCall, 1997). South of this suture, the Zagros and the Makran regions behave differently, highlighting how the subduction and collision settings differ. Indeed, while the convergence velocity accommodated by the Zagros collision increases progressively from northwest to southeast, the transition from the collision to the Makran subduction is marked by a jump from 9 ± 2 mm/yr to $\sim 19 \pm 2$ mm/yr (Vernant et al., 2004; Masson et al., 2007). The Zagros-Makran transition is thus expected to have a wrench motion of at least some 10 mm/yr. During late Cenozoic, Arabia and Eurasia continuously converged (figure 2; McQuarrie et al., 2003). Palinspastic reconstructions show how this continuous convergence was accommodated in Zagros and Makran during the last 30 My (Figure 2) suggesting that the Zagros-Makran transition zone must have been structured during the last ~ 15 My.

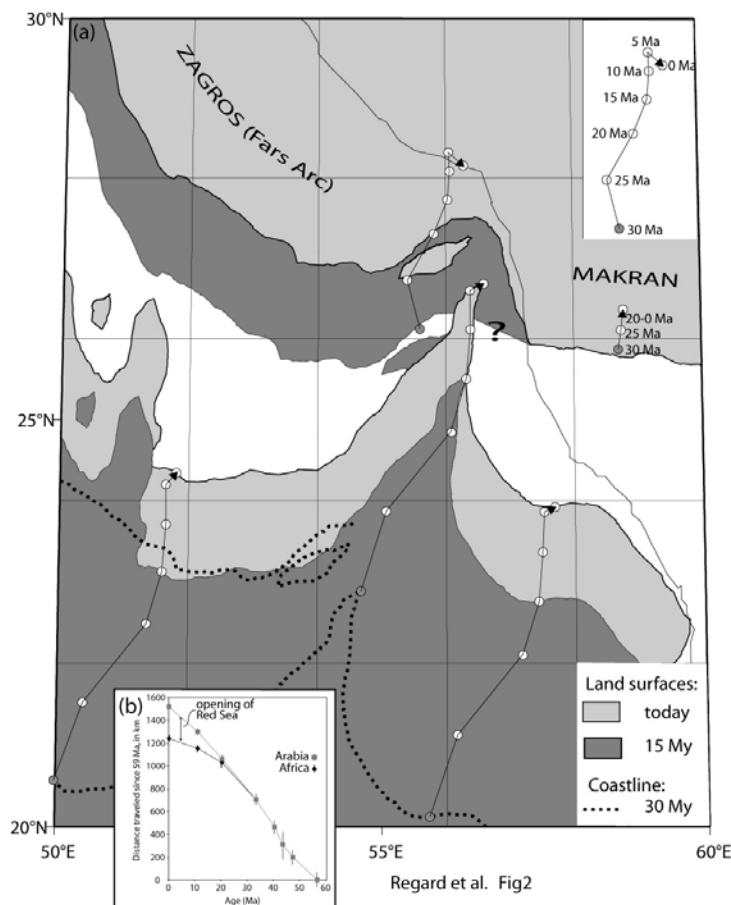


Figure 2. (a) Palinspastic reconstructions around the study area for the last 30 My, plates moving relative to Eurasia. The segmented lines with circles represent the displacement trajectories; see inset for stages division. The reconstruction is made after the ODSN plate reconstruction service: <http://www.odsn.de/odsn/services/paleomap/paleomap.html>. Reconstructions are based on block rotations calculated from magnetic anomalies (Hay et al., 1999; Soeding, 1999). Note that the ancient Makran shoreline cannot be estimated since it is constituted by an accretionary prism under construction; motion-segmented arrow is estimated by the Lut block reconstructed position. (b) Graph showing the position of a reference point (38°N, 48°E) representing Arabia with respect to Eurasia versus time, both including (grey boxes) and excluding (black diamonds) rotation describing the opening of the Red Sea, modified after McQuarrie et al. (2003).

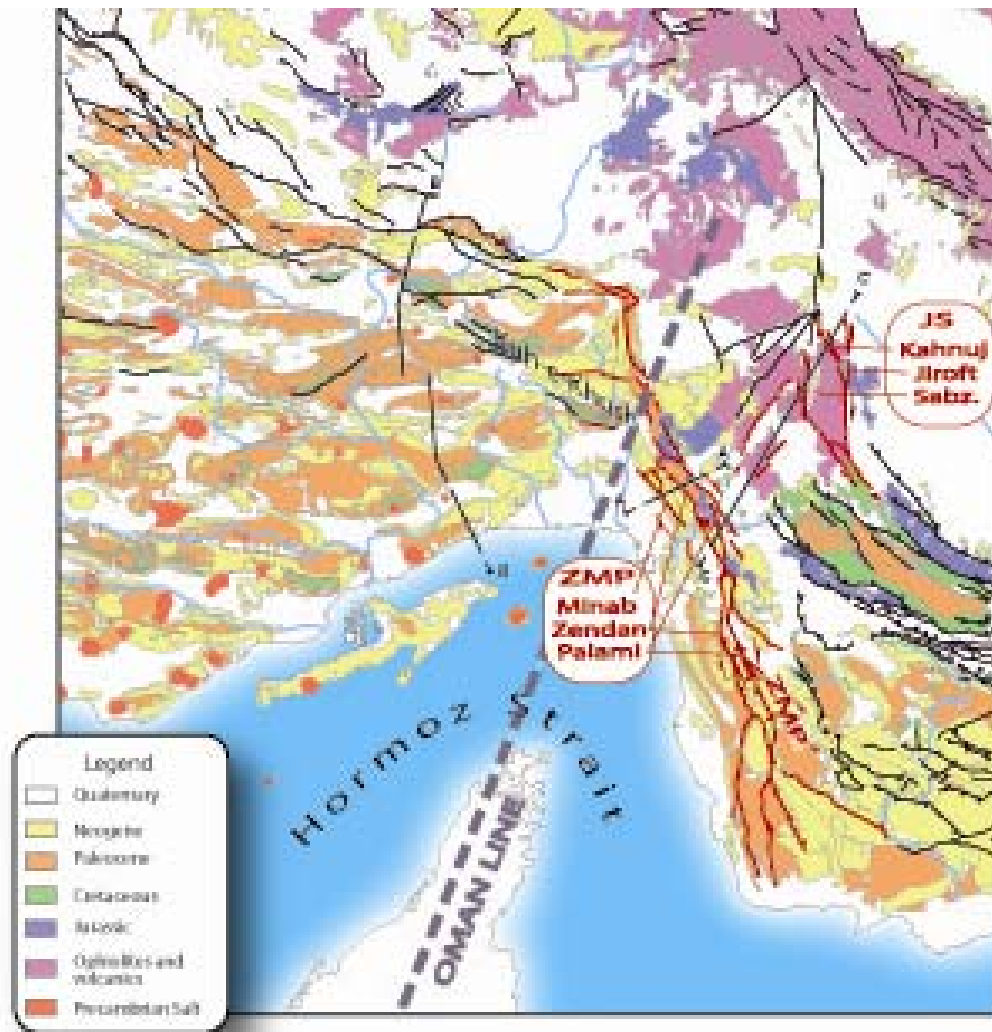


Figure 3. Geological map of the study area, modified after the 1:1 000 000 geological map of Iran. Faults in black are faults from the original drawing; in red are the active faults mapped by Regard et al.(2004), which are distributed in two fault systems, the Jiroft, Sabzevaran (abbreviated as Sabz.) and Kahnuj faults in the Jiroft-Sabzevaran fault system (JS); the Minab, Zendan and Palami faults in the Zendan-Minab fault system (ZMP). A-A' and B-B' are the cross-sections (Figure 5) from Molinaro et al. (2004). C-C' is the local tomography cross-section (Figure 8), from Yamini-Fard et al. (2007).

The transition takes place at the front of the mountainous Musandam peninsula (Hormoz Strait, Figure 1). Formed during Late Cretaceous, this mountain range not only magnifies the differences between the continent and the ocean, but also acts as heterogeneity within the colliding Arabia plate. It can be traced up to the Hormoz Strait, in a seismic profile running from Qeshm to Minab (Ross et al., 1986). Such a set-up suggests that the Oman peninsula may have interfered with the Zagros collision and be partly responsible for the curved shape of the Zagros Makran transition (Ricou et al., 1977; Kadinsky-Cade and Barazangi, 1982; Aubourg et al., 2008). Several other mechanisms have been proposed to explain this curved shape of the Fars Arc: (1) rotation of basement faults (Hessami et al., 2001); (2) it could be produced by a change in the style of accommodation of shortening from head-on shortening in the south-east to oblique shortening to the north-west of the Zagros fold-and-thrust belt (ZFTB) observed by Talebian and Jackson (2004); (3) a Jura style of

deformation in which the arcuate shape is controlled by the progressive lateral pinch-out of the basal Hormoz evaporates upon which the Zagros folds detach (Molinaro et al., 2005a).

The transition between Zagros and Makran is also often described in the literature as the ‘Oman Line’ trending N20°E and running northward from the Musandam peninsula (Kadinsky-Cade and Barazangi, 1982). It limits the continent to the east from the Oman Gulf oceanic crust to the west: it represents an inactive transform zone inherited from the Neotethys ocean opening (White and Ross, 1979). This transition marks the boundary between a region of high seismicity located in the north-west (the Zagros domain) and a region of low-seismicity to the east and is highlighted by the Musandam Peninsula trend. Formerly the Oman line was suggested to represent the transition between Zagros and Makran (Kadinsky-Cade and Barazangi, 1982), but it is now thought that this role is played by the Minab-Zendan Fault system, whose southern prolongation has been seen on seismic profiles from the Oman Gulf (Ravaut et al., 1998).

The presented multidisciplinary study aims at better determining the structure and kinematics of this key area. In particular, the Zendan-Minab fault system (Figure 3) is studied to help us understand why, as it seems to play a major role in the accommodation of the deformation, the associated seismicity is low. We also discuss the deformation related to this zone and see if it could be the result of the indentation by the Musandam Peninsula.

3 Results

3.1 Deformation pattern

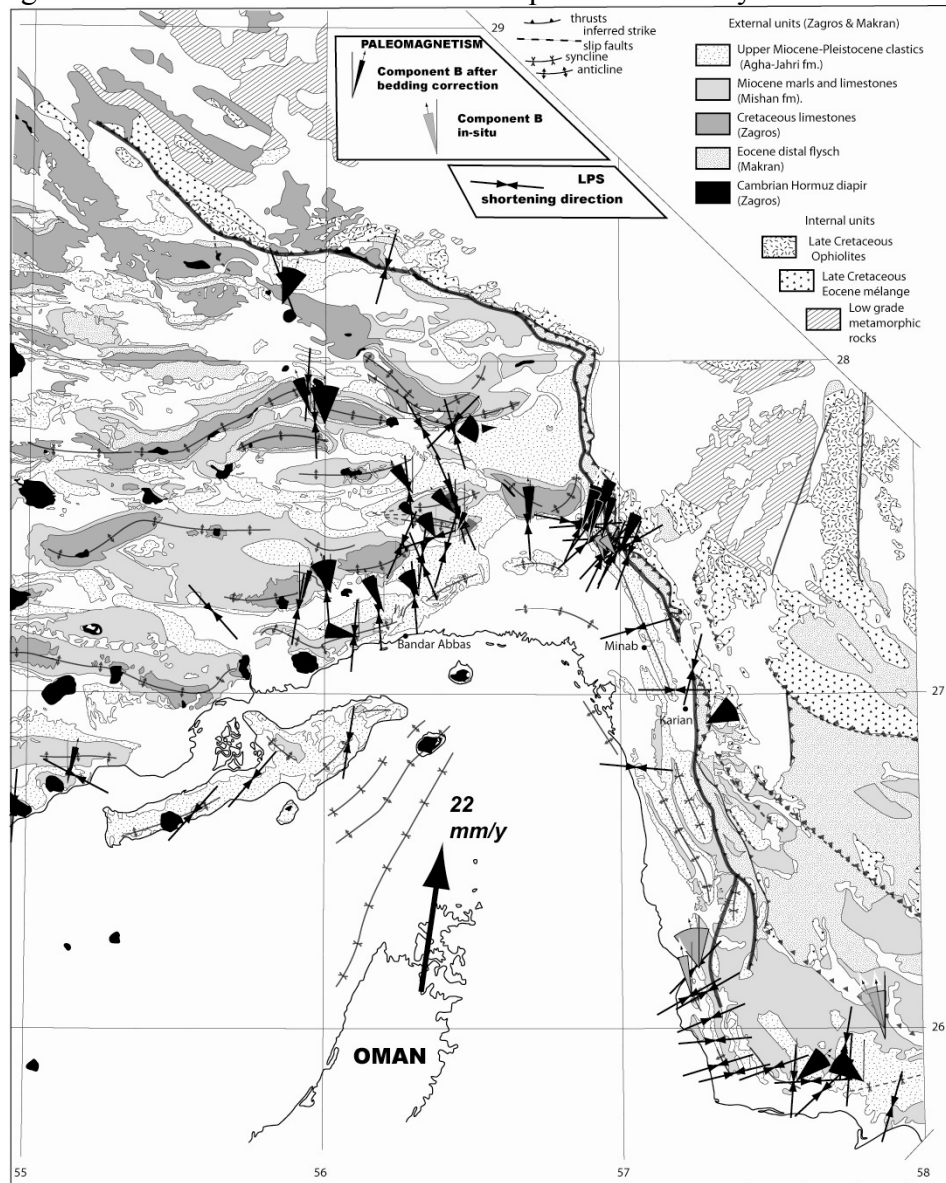
3.1.1 Tectonics

Using satellite images, and structural and geomorphic field observations, Regard et al. (2004) illustrated the study area’s present-day deformation pattern accommodated by faulting. The study area shows a distributed deformation pattern covering a wide domain (Figure 3). Six N- to NW-trending major faults were identified, each one displaying clear evidences of late Quaternary reverse right-lateral slip. They constitute two fault systems. The first one encompasses, from west to east, the Minab, Zendan and Palami faults (the ZMP fault system; Figure 3). The Zendan fault corresponds to the lithological boundary between the Zagros and Makran. The second one, the Jiroft-Sabzevaran (JS) fault system, comprises the Jiroft, Kahnuj and Sabzevaran N-trending faults (Figure 3). The ZMP fault system transfers the Zagros (continental prism) deformation to the Makran accretionary prism, whereas the JS fault system transfers some motion northward to the Alborz/Kopet Dagh convergence zone in northern Iran (Figures 1 & 3). Tectonic study and fault slip vector analyses indicate that two distinct tectonic regimes have occurred successively since the Miocene within a consistent regional NE-trending compression: (1) an upper Miocene to Pliocene tectonic regime characterised by partitioning between reverse faulting and en echelon folding; (2) a NE-trending σ_1 axis transpressional regime homogeneously affecting the region since upper Pliocene (Regard et al., 2004). The change is contemporaneous with a major regional tectonic reorganisation (Allen et al., 2004). This study provides evidence of active deformation that is not localised, but distributed across a wide zone. It accommodates the convergence and transfers it from collision to subduction by transpressional tectonics without any partitioning process in the present-day period.

3.1.2 Magnetism

Several studies using magnetic fabric data were conducted in the Fars Arc and in the eastern Makran (Bakhtari et al., 1998; Aubourg and Robion, 2002; Aubourg et al., 2004; Smith et al., 2005). In the Agha-Jari formation (Upper Miocene-Pleistocene silicoclastic

rocks), the magnetic foliation is parallel to the bedding, whilst the magnetic lineation strikes perpendicular to the horizontal shortening or layer parallel shortening (LPS). Several studies from other thrust belts (e.g., in the Pyrenees, Averbuch et al., 1992; Pares et al., 1999) suggest that the magnetic lineation records LPS with anticipation before any detectable folding.



Regard et al. Fig 4

Figure 4. Sum of magnetic studies on the Fars Arc and western Makran (Bakhtari et al., 1998; Aubourg et al., 2004; Smith et al., 2005); see text for explanations.

Near our study area, Aubourg et al. (2004) compared the magnetic fabric data with P-axes earthquakes focal mechanisms and found a good agreement west of the Zagros-Makran transition, contrasting with significant differences in the east. Data collected during the last ten years are summarised in Figure 4. To the west, in the Fars Arc, the general trend is a shortening direction (LPS) close to the GPS convergence direction (N-S), with slight anticlockwise rotations. Just west from and within the Minab-Zendan fault system, the shortening direction is roughly normal to the structures whereas clockwise rotations are recorded. To the east (within the Makran), data are sparse and do not show a clear signal, despite many LPS directed parallel to the N-S convergence direction.

Smith et al. (2005) and Aubourg et al. (2008) measured palaeomagnetic data in the Agha Jari formation (Mio-Pliocene) to document vertical axis block rotations. The pre-tilting palaeomagnetic component B documents the rotation that occurred between the age of Agha-Jari Fm. and recent time (Figure 4). At first glance, it is apparent that clockwise and counterclockwise rotations of small magnitude (typically less than 20°) occurred respectively in the eastern and western Zagros-Makran transition zone. If the block rotation is removed, the LPS directions are in good agreement with the overall convergence direction. This suggests that the present shape of the Zagros-Makran transition zone, oblique to the convergence direction, has been acquired only recently (since Mio-Pliocene).

In sum, palaeomagnetic and magnetic fabric data (LPS) document the ~N-S convergence, except near the Zagros-Makran transition zone, where the structures have experienced recent clockwise rotations that may continue at present (Figure 4). These rotations agree with a wrench zone that is not localised on a single structure but over an area that is some tens of kilometres wide. The Fars Arc exhibits slight anticlockwise rotations suggesting it has experienced some indentation since Middle Miocene (Figure 4).

3.2 Balanced cross-sections

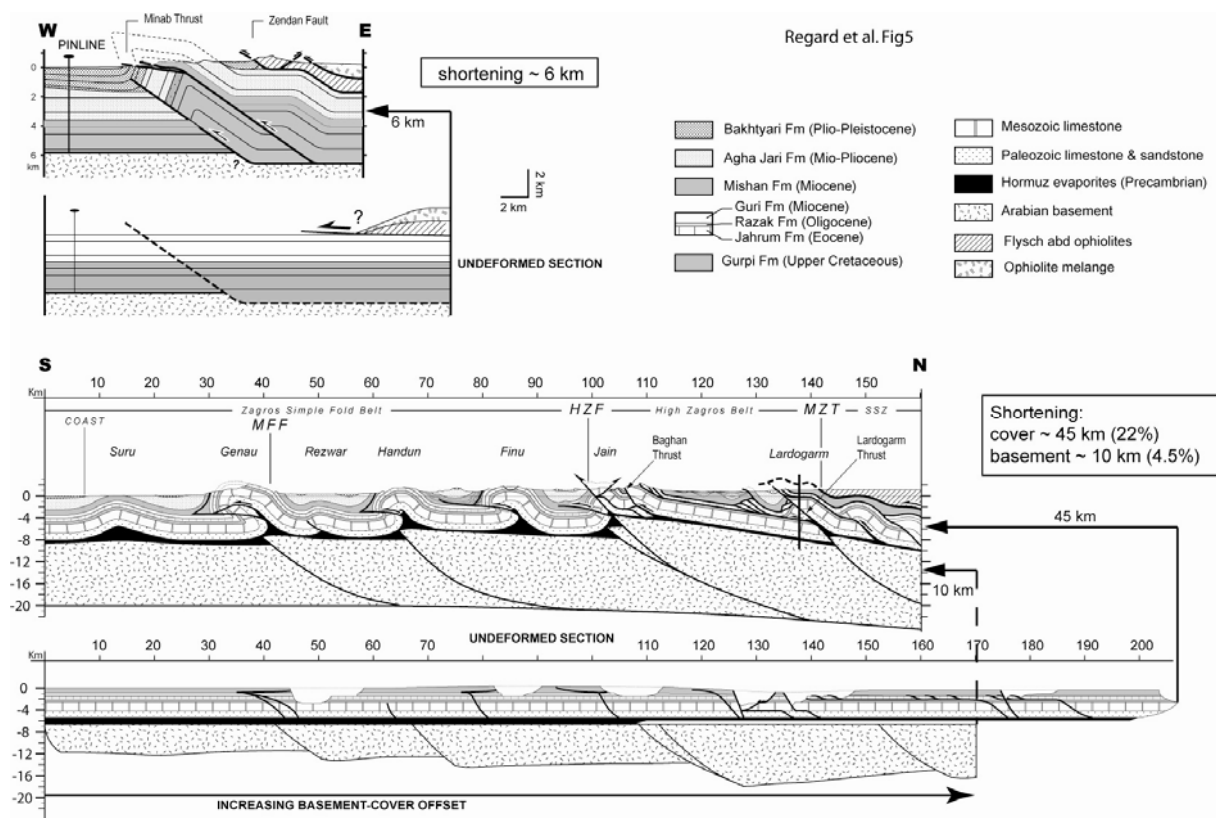


Figure 5. Balanced cross-sections, from Molinaro et al. (Molinaro et al., 2004; Molinaro et al., 2005a). See Figure 3 for profile location. AA' - cross-section through the Minab-Zendan Fault System. BB' - cross-section from Bandar Abbas to Hajiabad, southeastern Zagros. MFF, Main Front Fault, HZF, High Zagros Fault, MZT, Main Zagros Thrust, SSZ, Sanandaj-Sirjan Zone.

Molinaro et al. constructed two cross-sections on each side of the Zagros-Makran transition (Molinaro et al., 2004; Molinaro et al., 2005a). The contribution of this work is not only to provide quantitative shortening values but also to reveal how the deformation is accommodated. The section on the eastern side of the transition indicates some 6 km shortening in front of the Zendan fault, affecting only the Tertiary cover, over a décollement

approximately 6 km deep (Figure 5; section AA' in Figure 3). The shortening is measured perpendicular to the Zendan fault, i.e. along a N150°E-trend. In the south-east Zagros, the Bandar Abbas–Hadjiabad section (BB' in Figure 3) displays two different N-S shortening values of 10 and 45 km, respectively, for the basement and the cover (Figure 5). In particular, with this section the authors document two main steps in the evolution of the Zagros fold-thrust belt. In the first Mio-Pliocene stage the deformation was thin-skinned in style, with a décollement lying approximately 8-9 km deep. In the second Pliocene to Recent shortening stage, the basement must be involved through major thrust faults, inferred from focal mechanisms and observation of steps in the general topography and structural elevation of the Zagros mountains. These faults ramp up through the cover and cut the former folds obliquely: the best example is the Kuh-e-Khush (Figure 2). This obliquity can be due either to rotation of folds, reactivation of old basement structures or stress rotation. Geographically, to the west, in the Zagros, deformation is involving the entire crust with folding in the cover controlled by the basal Hormoz salt layer and major thrusting in the basement. To the east on the other hand, folding is controlled by a décollement located at 6 km depth and the basement does not appear to be involved in the deformation.

3.3 Seismotectonics and deep structure

3.3.1 Seismotectonics

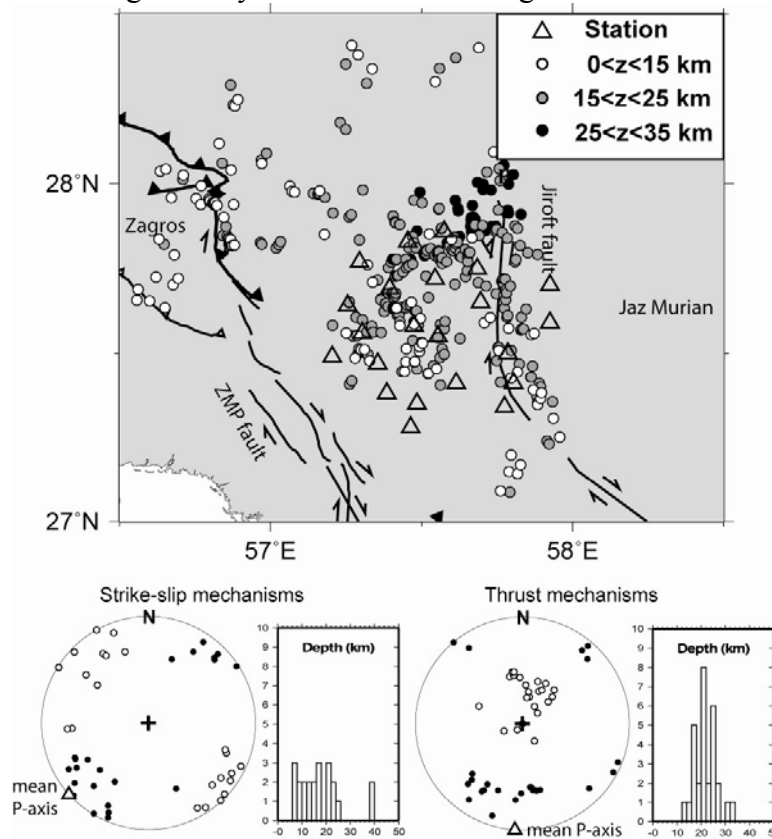
Yamini-Fard et al. (2007) installed a dense seismological mobile network of 24 stations for 8 weeks in 1999, in the area of Bandar Abbas, to locate precisely the microseismicity of the area and calculate focal mechanisms (Figure 6). In addition, they realised a tomographic traverse, with 25 stations from Hadjiabad to Minab and the Makran ranges (Figure 7).

The microearthquake distribution around the transition between the Zagros continental collision and the Makran subduction is restricted to the west of the Jaz Murian depression and the Jiroft fault (Figure 6). No earthquakes seem to be related to the Zendan-Minab-Palami fault system. Most of the shallow seismicity is related either to the Zagros mountain belt, located to the west, or to the Sabzevaran-Jiroft fault system, located to the north. The depth distribution of the microearthquakes increases northeastward to an unusual value for the Zagros of 40 km. Two dominant types of focal mechanisms are observed in this region: low angle thrust mostly restricted to the lower crust (at depths between 15 and 30 km) and strike-slip at shallow depth (10-20 km, Figure 6). Both are consistent with NS to NE-SW shortening.

3.3.2 Crustal seismic structure

Teleseismic P-wave travel times, from ~50 earthquakes, were calculated along a profile that crosses the Minab-Zendan Fault system at three different locations. The orientation of the profile was governed by accessibility and safety of the road. We observe a large delay in the travel time residual every time the profile crosses the ZMP (Figure 7). The inversion of the travel time residuals performed by Yamini-Fard (2003) highlights perturbations relative to a homogeneously-layered velocity structure. In the first layer (associated with the crust), two low-velocity anomalies are related to the ZMP fault zone. The deeper layers related to the upper mantle show a slow velocity in the west relative to a fast velocity in the east of the ZMP. If we project the residual on a profile perpendicular to the ZMP function of the distance to the ZMP (Figure 7), we see a clear offset of up to 1 sec at the location of the ZMP. For stations located on the Makran block, we observe a decrease with the distance to the ZMP, which is also related to a south-eastward orientation of the profile. Because the crustal structure is 3D, and the slab is dipping northward beneath the Makran, it

is likely that the offset decreases southward. The strong offset exactly related to the ZMP, however, indicates a strong velocity contrast between Zagros and Makran.



Regard et al. Fig 6

Figure 6. Map of the microseismicity recorded for the period 17 November 1999 to 6 January 2000 by Yamini-Fard et al. (2003; 2007). They computed 59 focal mechanisms that can be divided into two groups regarding their mechanism: strike-slip (horizontal T-axis) or thrusting (vertical T-axis). They are represented and lead, respectively, to $\sim N45^\circ E$ -trending and $\sim N$ -trending mean P-axis. Interestingly, thrust mechanisms occur at depths (15–35 km) greater than strike-slip mechanisms (5–25 km); black and white dots are P- and T-axes, respectively (redrawn after Yamini-Fard et al., 2007).

Yamini-Fard (2003) also computed teleseismic receiver functions. The P-S converted phases usually image the Moho discontinuity well. Their interpretation is not straightforward: the receiver function data are complex and cannot be easily used to draw a Moho profile. This complexity probably comes from the departure of the flat-layered structure that is used as an initial model and generates complex wave propagations in the crust.

Finally, Yamini-Fard et al. (2007) computed a local 3D crustal velocity structure and relocated simultaneously the local earthquakes inverting the travel times of local seismicity (Yamini-Fard et al., 2007). The resulting velocity structure suggests a high velocity body dipping northeastward (Figure 8). An important result is that no seismicity appears to be associated with the Zendan-Minab-Palami fault system, suggesting that the transition between the Zagros collision and the Makran subduction is not associated with a sharp transform fault. Instead it is associated with a progressive transition located in the lower crust. The shallow right-lateral strike-slip faulting is the response of the upper crust to the shortening. This

‘partitioning’ in depth is likely related to the difference in the strength of the upper and lower crusts.

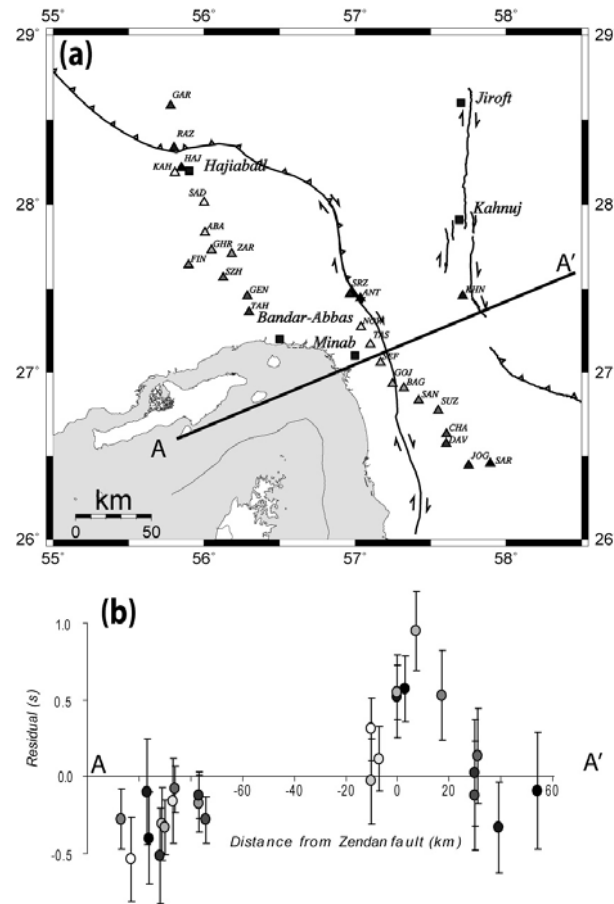


Figure 7. Teleseismic travel-times residuals at station along the Minab profile. (a) Location of seismological stations. (b) Residual values, given by reference to the average residual (in s), vs. eastward distance to the Zendan fault. Redrawn from Yamini-Fard et al. (2003; in prep). Symbols colours are varied equally in the map and the residual graph.

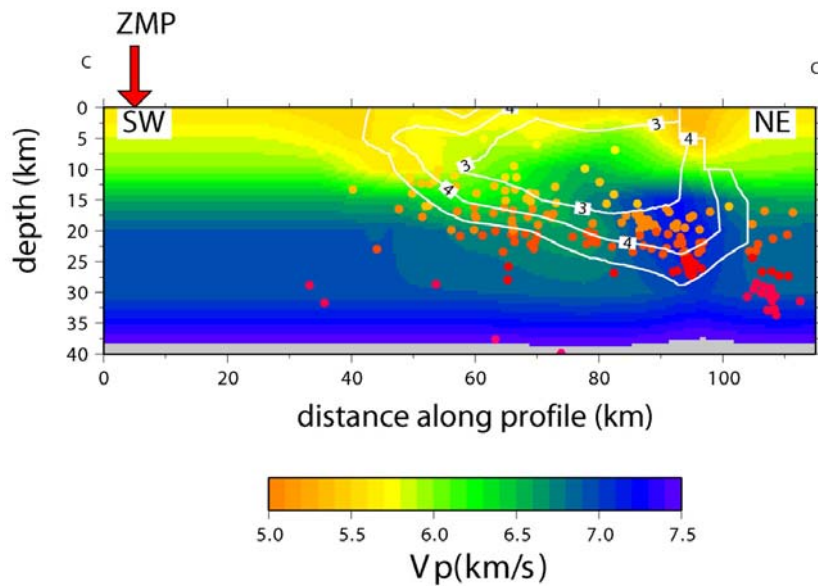


Figure 8. Cross-section of the 3D velocity structure trending SW-NE computed from local travel time residuals: see Figure 3 for localisation. Results are reliable for a spread function less than 5 (white contour). The hypocentres are reported. There is a clear indication of a northward dipping anomaly related to the seismicity (Yamini-Fard et al., 2007).

3.4 Modern kinematics

3.4.1 GPS

Vernant et al. (2004; updated by Masson et al., 2007) used a network of 27 GPS sites to establish the current large-scale deformation rates within Iran. The network was measured three times, during September 1999, October 2001 and October 2005. This work provided a useful overview of Iranian geodynamics. The authors then divided Iran into various rigid blocks. They conclude that to the west, the Zagros is undergoing 9 ± 2 mm/yr of shortening, in a direction close to N-S. To the east, the Makran subduction accommodates 19 ± 2 mm/yr of N20°E-trending convergence. The Makran-Zagros transition zone should thus accommodate some 11 ± 2 mm/yr of right-lateral movement.

Bayer et al. (2006) used a denser network focused on the Zagros-Makran transition zone. It consists of 15 stations, with an average distance of ~ 60 km, which were measured in 2000 and 2002. The GPS-derived velocity field can be expressed in different useful frames: fixed Eurasia, fixed Central Iran or fixed Arabia (Figure 9). When expressed in Central Iran fixed frame, the velocity directions are more or less parallel to the convergence velocity. There is no clear divergence from the Musandam peninsula (Oman), contrary to what would be expected if Musandam was acting as an indenter, as proposed by Kadinsky-Cade and Barazangi (1982; figure 9).

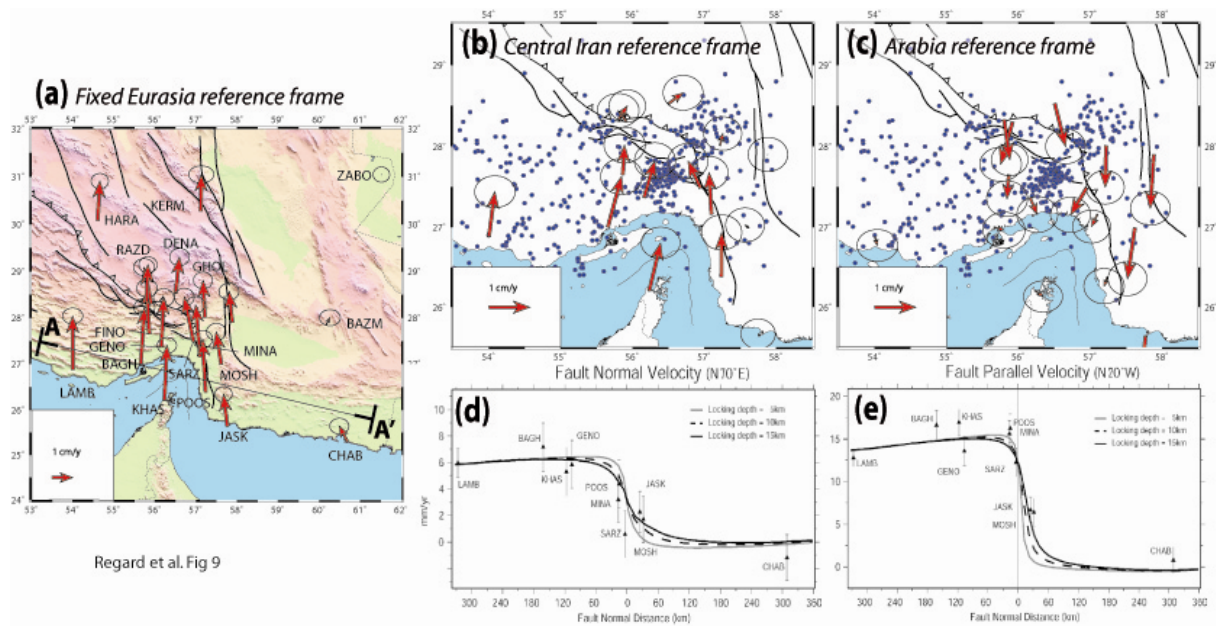


Figure 9. GPS data for the study area (Bayer et al., 2006). (a) GPS velocity and their 95 per cent confidence ellipses in Eurasia fixed reference frame. (b and c) close-up into the study area in, respectively, central Iran fixed reference frame and Arabia fixed reference frame; dots represent instrumental seismicity. (d and e) GPS velocity profiles, normal and perpendicular, respectively, to the Zendan-Minab fault trend (AA' in map a). Lines refer to best-fit deformation with a block model (see Bayer et al., 2006 for details).

Assuming a rigid block model, Bayer et al. (2006) computed the motion accommodated by the Minab-Zendan-Palami fault system. They found 15 mm/yr and 6 mm/yr for the motions parallel or perpendicular to the direction of the fault, i.e. N160°E (Figure 9). In addition, they estimated the strike-slip motion of the Jiroft-Sabzevaran fault system (N-trending) to be 3.1 ± 2.5 mm/yr. The Minab-Zendan-Palami fault system motion is estimated in its southern part, where the entire Zagros-Makran motion must be accommodated

(Regard et al., 2004), whereas in its northern part, Zagros-Makran transition zone deformation is distributed over the two fault systems. The 15 mm/yr-MZP fault system displacement rate must therefore encompass the 3.1 ± 2.5 mm/yr of the Jiroft-Sabzevarn fault system calculated by Regard et al. (2005a, see next paragraph).

Geodetic data show that almost all the convergence is accommodated in the East by the Makran subduction zone, while only half of it is accommodated in the west by the Zagros. The Zagros-Makran transition zone clearly accommodates ~ 15 mm/yr of differential motion; the transpressive character of the transition zone is because of the fault obliquity relative to the overall plate convergence direction. Geodesy does not provide evidence of a rigid indentation of the Musandam peninsula into Iran that would be represented by a velocity field pattern divergent from the Musandam Peninsula.

3.4.2 Tectonics and geomorphology

As described earlier, Regard et al. (2004) provided evidence of two fault systems accommodating the relative velocities in the northern part of the study area (whereas the results of Bayer et al., 2006's concern the southern part of the system). Tectonic and geomorphic analyses combined with cosmogenic nuclide-dating (^{10}Be) have revealed a total right-lateral slip rate of 4.7 ± 2.0 mm yr $^{-1}$ to 6.3 ± 2.3 mm yr $^{-1}$ for the ZMP fault system, depending on the ages of offsets, and 5.7 ± 1.7 mm yr $^{-1}$ for the JS fault system (table 3 in Regard et al., 2005a; Regard et al., 2006). They evaluate the total motion accommodated across the area to 11.3 ± 3.9 mm.yr $^{-1}$ or 13.1 ± 4.3 mm.yr $^{-1}$ in a direction $\text{N}10 \pm 20^\circ\text{E}$.

The total shortening at the west front of the ZMP fault system is estimated to be ~ 6 km (Figure 4) since the Mio-Pliocene (~ 5 My, Molinaro et al., 2005a), and implies an average shortening rate in the order of 1 mm.yr $^{-1}$.

4 Discussion

The work presented here is a compilation of data collected by different means. It gives a unique insight into a subduction-collision transition zone current dynamics. In particular, important questions arise, such as what is the lithospheric structure? where is the main structure? does the Musandam Peninsula act as an indenter?... In order to give a coherent view of this transition we first describe what we do know about its structuration, then we try to assess the question of its modern kinematics and the timing of its set-up before inferring its future through comparison with laboratory experiments and other subduction-collision transitions.

4.1 Crustal and lithospheric structure

Before Arabia and Iran began to collide, probably late in Oligocene, the area was occupied by a continuous subduction zone. The subduction of the continental Arabia to the west provoked a collision, whereas to the east the oceanic part of the Arabian plate still subducts. Under the Zagros collision the plate probably broke and the oceanic part may have sunk deep into the mantle (Molinaro et al., 2005b). More to the east, in the study area, it is actually difficult to know if the nearby Zagros underwent such a slab break-off or if the subducted slab is still attached. In particular, the transitional area is wide, which pleads speculatively for a gentle transition at depth, compatible with a continuous deep slab (Regard et al., 2005a; Regard et al., 2005b). Closer to the surface, seismological data display a clear view of a NE-dipping surface (Figure 8). This plane dips $\sim 15^\circ$ and is likely to originate at surface near the ZMP fault system (Figure 8) (Yamini-Fard et al., 2007). This plane is associated with an important microseismicity with NE-trending P-axes, showing thrusting at depth (figure 6) (Yamini-Fard et al., 2007). It would thus correspond to an active crustal-scale

thrust, separating a Zagros-related part in its footwall from Makran formations in its hanging wall.

The system tectonics appears more complicated in the uppermost part. It is dominated by folds and faults organised in two fault systems: (1) the ZMP fault system to the southwest and (2) the JS fault system to the north-east. (1) The NNW-trending ZMP fault system is associated with an echelon folding and constitutes the lithological boundary between Zagros and Makran (Regard et al., 2004). It presents high-velocity anomalies (1s residuals, Figure 7) (Yamini-Fard, 2003). It is made of numerous and highly-segmented faults. The system's western faults dip ENE whereas the eastern ones dip WSW, giving a flower-structure-like superficial organisation (Regard et al., 2004). This system could act as a developing crustal-scale strike-slip fault, with infilling by dense material, but these observations do not agree with the balanced cross-section that implies an 8km-deep décollement surface that should extend a couple of kilometres eastward from the ZMP fault system. This apparent discrepancy will be resolved later. (2) The N-trending Jiroft-Sabzevaran fault system does not appear to be marked by any seismicity alignment even if the local seismicity level is high (Yamini-Fard, 2003). The faults are strike-slip with a little component of vertical motion. The fault system is partly linked to the south with the tectonical Makran northern boundary, south of the Jaz Murian depression, and partly to the ZMP (Regard et al., 2004). To the north the system seems to pursue northward to the Nayband and Gowk faults which mark the boundary between Central Iran and the Lut Block (Walker and Jackson, 2002).

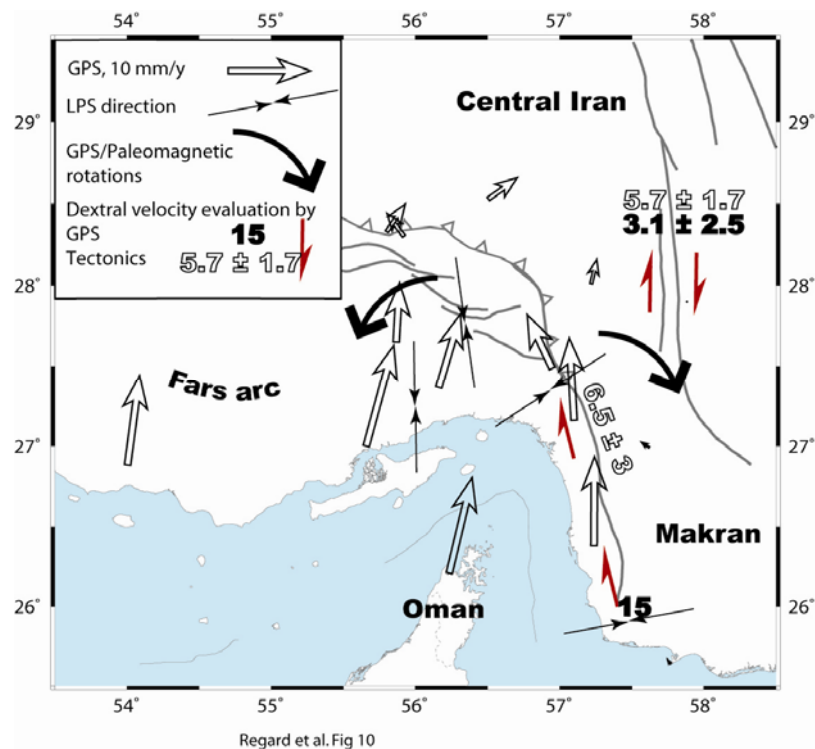


Figure 10. Sum of observations at surface. GPS is indicated in the Central Iran fixed reference. See text for deep-structure observations.

4.2 Surface structural setting and modern kinematics (Map view)

The current deformation at surface and close to the fault systems is shown to be caused by a NE-trending main compressional direction by seismology and active tectonics (Regard et al., 2004; Yamini-Fard et al., 2007). Active tectonics also indicate that

convergence is accommodated nearly equally by the two fault systems, the deformation being distributed within each fault system instead of being localised (Regard et al., 2005a).

On a wider scale, the palaeomagnetic data show that rotations occurred both clockwise to the east and anticlockwise to the west of the transition zone. This could plead for an indenter role of the Musandam peninsula (Aubourg et al., 2004, 2008). On the other hand, the GPS velocity field does not show any divergence away from the 'indenter', and this would suggest there is no rigid indentation in the area (Figures 9 & 10). Tectonic observations also do not favour the Musandam Peninsula indenter hypothesis, since they indicate that the motion between Arabia and Makran is accommodated only by one transcurrent fault system (ZMP), on which all the relative motion is accommodated, as indicated by the similarity in GPS and tectonic velocities.

Indeed, the global motion accommodated by the transition zone fault systems is evaluated by GPS to be 15 mm/yr, close to the evaluation from tectonics from 11 to 13 mm/yr. GPS and tectonics agreement is not so good on the part accommodated by the Jiroft Sabzevaran fault system, whose transcurrent motion is evaluated to be 3.1 ± 2.5 mm/yr or 5.7 ± 1.7 mm/yr respectively (figure 10). The discrepancy comes from the loss of the elastic component away from the network, whose easternmost station is close to the Jiroft Fault, as highlighted by recent results (Peyret et al., in prep).

4.3 Two stages post-Miocene evolution

Some of the studies presented here highlight a two-stage scenario for the recent (since Miocene times) evolution of the area. First, magnetic studies indicate that the transition shape, oblique to the convergence, has been acquired recently, since the Mio-Pliocene. Before the transition structural set-up, the deformation recorded by magnetism was roughly coherent with the overall plate convergence. Superimposed on this, some moderate rotations, clockwise to the east and anticlockwise to the west, may account for a slight indentation by the Musandam Peninsula. Second, a major change in tectonics was also recorded. As emphasised before, the balanced cross-section of the Minab fold proposed by Molinaro et al. (2004) appears not to be compatible with modern kinematics and structure. The Minab fold may have been formed during a former deformation stage. In addition, palaeostress determinations by Regard et al. (2004) show a stress-orientation change in the Pliocene. The authors suggested that it corresponds to a change from a partitioned convergence accommodation through folds and reverse faults (ZMP) to non-partitioned convergence accommodation through the ZMP transpressional faulting. The best way to combine these results (tectonics, structure, and kinematics) is to assume that the flat thrust shown by balanced cross-sections has been cut through by a more vertical fault, possibly evolving to a flower structure near the surface. This fault is likely to carry exotic slices like the Palami range lying between the Palami and Zendan faults.

4.4 Comparisons with comparable settings, both in laboratory and in nature

Cotton and Koyi (2000) proposed a sandbox experiment that interestingly mimics the study area even if it was not intended to reproduce it (Figure 11). The experiment comprises a sandbox undergoing N-S compression; the sand is lying over a frictional substrate in the western part whereas it is underlain by a ductile level in its eastern part (Figure 11). Even if it was actually designed for basin tectonics, we could interpret it in terms of lithospheric structure. The frictional vs. ductile substrate should be compared to the collision vs. subduction convergence settings. In this experiment, the eastern range (over ductile substrate) extends more to the south than the western range. Between the two ranges a transfer zone is produced which is noticeably made of two N-trending strike slip faults: (i) a south-western

one connecting the deformation zone of the western range (over a frictional substrate) to the frontal thrust of the eastern one; (ii) a northern one that connects the northern part of the experiment with the backstop of the eastern range (Figure 11). Comparison of this scheme with the structural setting of the Zagros-Makran transition zone highlights many similarities; in particular, the faults (i) and (ii) probably represent the ZMP and JS fault systems, respectively (Figure 11). Moreover the experiment cannot explain the curvature of the Fars Arc (south-eastern Zagros), whereas in the experiment the range over the frictional substrate has a linear trend (Figure 11). A possible explanation for this is that in the Fars Arc the curvature is due to the underthrusting of the Musandam Peninsula.

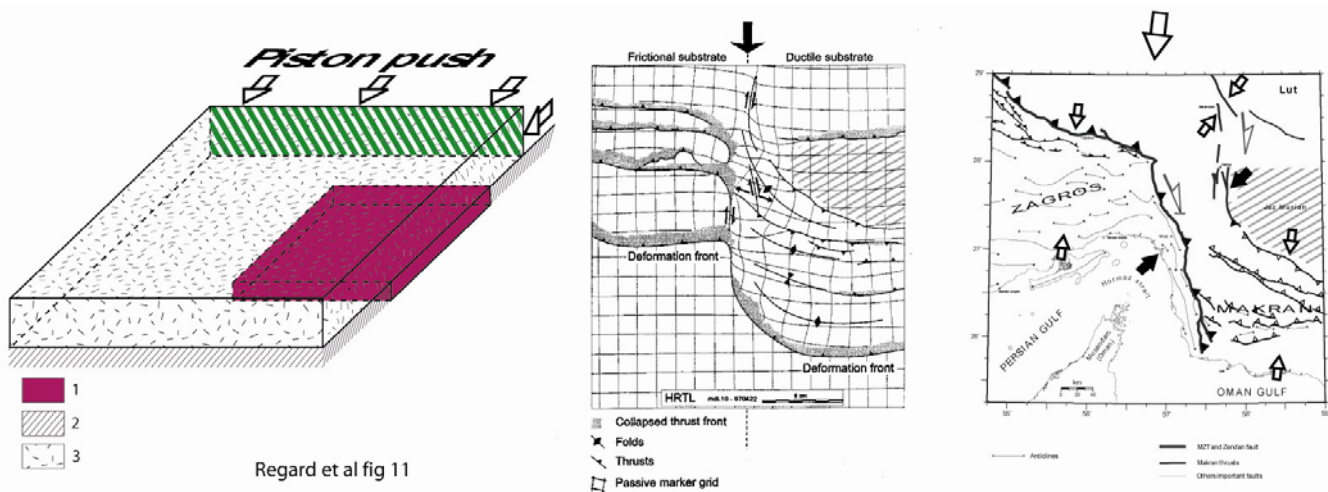


Figure 11. Sandbox experiment realised by Cotton and Koyi (2000). (a) The setup consists of a box filled with sand (3) over a rigid basement (2) which is partly replaced by a low viscosity layer (1). The sand layers experience convergence owing to piston push. (b) The experimental result shows that the structures propagate further over the viscous basement than over the rigid basement; a transition zone is created. (c) Structural scheme of our study area, with strain arrows, which is much like the experimental result (b).

Another transition between subduction and collision can be found at the other Makran end. Some of us have already initiated this discussion (Regard et al., 2005a). There, the transfer zone is constituted by three single faults, the Chaman, Ghazaband and Ornach-Nal faults (Figure 12). The system connects the Makran accretionary prism to the Pamirs (Panjshir Fault) (Lawrence et al., 1992). The overall system is thought to accommodate between 25 and 35 mm yr⁻¹, following geological evidence (Beun et al., 1979), and 40 mm yr⁻¹, after the NUVEL-1 model (DeMets et al., 1990). The most important part of the deformation is transmitted to the inner Makran and there is no evidence of active deformation transmission to the frontal, offshore, Makran thrust. The transition zone is more mature than the Zagros-Makran transition zone. Indeed, it is known to be much older (20–25 Myr instead of 5 My or less) and its length (more than 1000 km) implies a considerable slab-stretching such that the slab must no longer be continuous between Markan and Pamirs. Consequently this system could be viewed as a possible future for our study area. In particular, it is noteworthy that the accommodation by two or three disconnected systems characterises the transition zone as well as in the Cotton and Koyi (2000) experiment and at the Zagros-Makran transition (Figures 11 & 12). Some partitioning also occurs, for example, between the Chaman strike-slip fault and the Sulaiman fold belt (Lawrence et al., 1992; Davis and Lillie, 1994). In turn, the maturity is expressed by the localisation of the deforming structures that are long, low-segmented faults in contrast with the highly-segmented fault systems in the Zagros-Makran area (Regard et al., 2005a).

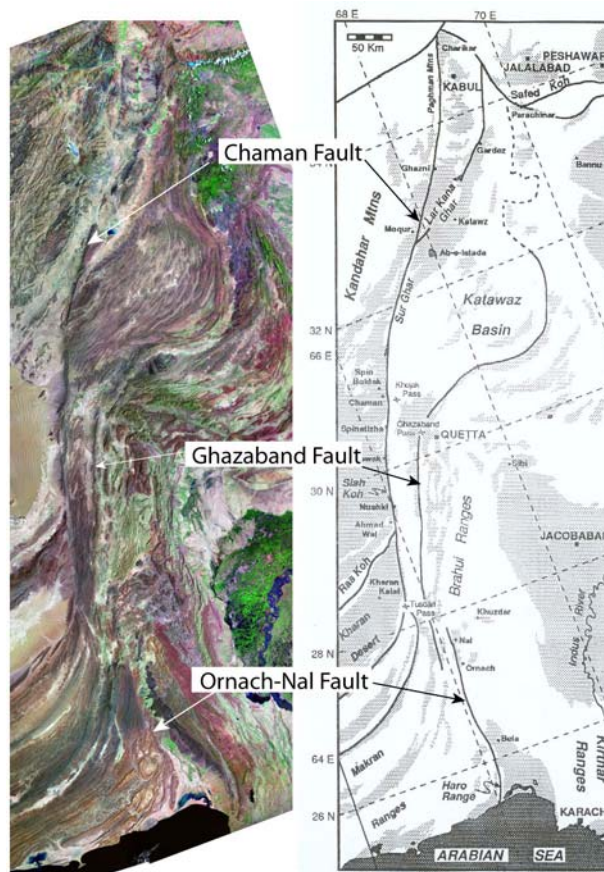


Figure 12. Landsat image of the Chaman fault (bands 7, 4 and 2) and its tectonic interpretation, after Lawrence *et al.* (1992). Note that the transfer zone is constituted by three continuous but disconnected faults: the Chaman, Ghazaband and Ornach-Nal faults.

4.5 Synthesis

The Zagros-Makran transition zone evolution through time has probably been influenced by an inherited structural setting. For a better understanding of the way it recently evolved, a simplified scenario is proposed in Figure 13. Actually, the way this area is deforming is comparable to the Makran-Pamir transition and the laboratory experiment. Two characteristic fault systems are found to the south-west (Zendan-Minab-Palami fault system) and to the north-east (Jiroft-Sabzevaran fault system). To the east the Makran deformation expresses the same pattern as in the experiment and at the eastern Makran bound, but to the west, the Fars Arc shape disagrees with the experiment. We hypothesise that this is due to the complexity introduced by the Musandam Peninsula, topographically much higher than the surrounding parts of Arabia.

The first fault system (ZMP) currently trends N160°E, oblique to the convergence. It is made of three highly-segmented faults that are the possible expression at surface of a flower structure that changes to an oblique thrust at its northern bound. Seismology indicates that it is correlated by a strong discontinuity at depth and that near its northern termination its deep structure is a north-east dipping plane. In this scheme some 6-km structure-normal shortening occurs that could be the result of a former strain distribution or of a slight deformation partitioning, with a frontal fault accommodating up to 5 mm/yr of shortening, as indicated by the recent results of Peyret *et al.* (in prep). The 6 km-deep décollement proposed by Molinaro *et al.* (2004) may therefore now branch at depth to the flower structure. We propose that its central fault (Zendan) represents the main boundary between Zagros and Makran.

The second fault system (JS) trends N-S. It probably connects to the north to a well-known strike-slip system bounding the Lut block to the west. To the south its deformation probably transfers partly to the northern Makran tectonic boundary and partly to the ZMP fault system, as suggested by the laboratory experiment of Cotton and Koyi (2000).

Of the ~19 mm/yr differential convergence rate, some 3 to 6 mm/yr are accommodated by the JS fault system and ~6-7 mm/yr in the ZMP fault system at the Minab latitude, increasing to ~15 mm/yr to the south; this increase corresponds to the progressive deformation transmission from the JS fault system to the ZMP fault system. Note that if one part of the JS accommodated deformation is transmitted to the Makran northernmost thrust, the 15 mm/yr strike-slip deformation observed to the south of the ZMP fault system is not fully explained by addition of the ZMP and JS motions (max 13 mm/yr). This discrepancy is not yet resolved.

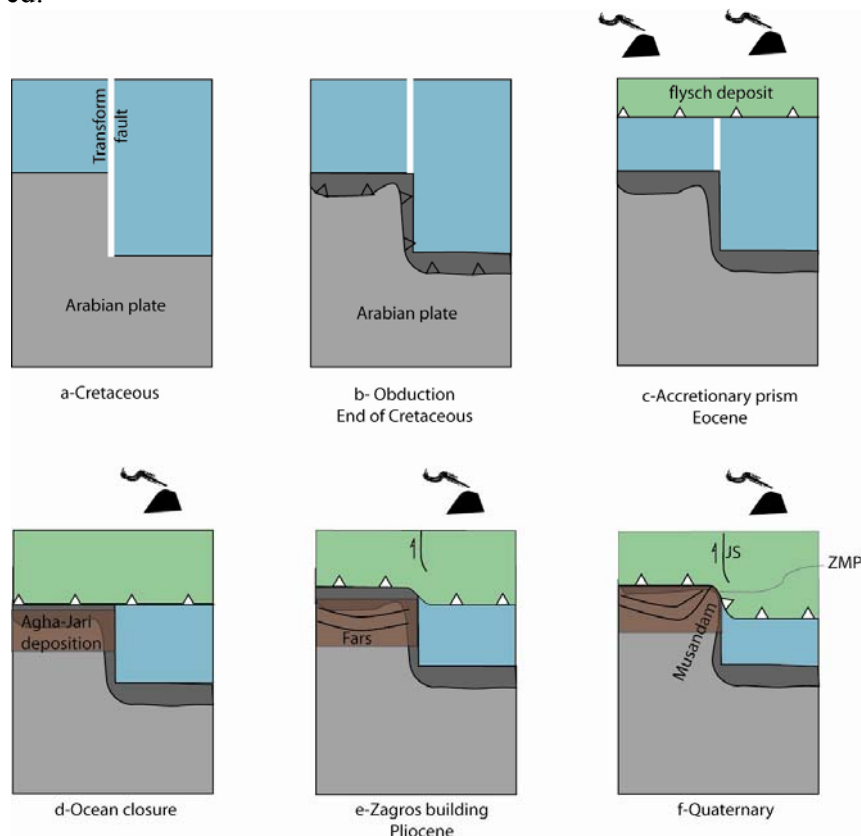


Figure 13. Sketch of the study area history. 1- Initial setting: a former passive margin south of the Tethys, cut by a transform fault. 2- Obduction occurred near the end of Cretaceous. 3- The Tethys northern margin was subducting for a while when the accretionary prism began to be built (Eocene). 4- Subsequently to ocean closure and emergence, Agha Jari deposited. 5- Zagros building during Pliocene; onset of Zagros-Makran syntaxis. 6- Modern setting; JS and ZMP are, respectively, the Jiroft-Sabzevaran and Zendan-Minab-Palami fault systems. The topographic Musandam high causes the Fars Arc curvature.

The data presented here provide evidence of post-Miocene system evolution (Figure 13). The overall oblique structure is from recent (less than 5 My) setting as attested by magnetism and tectonics. The set-up time is contemporaneous with a major change in the Middle East tectonics and with Zagros topography-building initiation (Allen et al., 2004). During this set-up, Zagros and Makran, originally continuous, differentiated. Interestingly this differentiation occurred at the time when deformation in Zagros passed from thin-skinned to thick-skinned (Molinaro et al., 2004), that is, very differently from the Makran, where only the sediment cover is scraped off. It is very tempting to relate the onset of the Zagros-Makran

transition zone to the initiation of thin-skinned tectonic shortening in Zagros from then on very different from the Makran tectonic style, where only the sediments overlying the oceanic crust are affected by deformation. The faults and folds constituting the system are currently in a young stage and they sometimes undergo some change as attested by stress tensor orientation changes. Nowadays, the system is divided into two fault systems that will endure while their internal organisation will simplify to localise in a single and continuous structure, even if some partitioning is likely to continue. Obviously, such a transition is a lithospheric-scale deformation zone.

5 Conclusion

This review of studies about the Zagros-Makran transition zone clarifies many points, giving a coherent overview of its structural setting and behaviour.

- The location of this transition is dictated by the past. Indeed, it corresponds to a coastline offset by a transform fault at the ocean opening time (Figure 13a).
- There is no evidence that currently the two deformation zones, Zagros and Makran, are connected by a transform fault. Numerous faults accommodate the deformation, organised in two fault systems. Some of the faults could be of crustal extent.
- The current stress state is transpressional with a NE-trending σ_1 ; the associated strain is strike-slip with some transpressional component.
- An important change in how the tectonics works occurred somewhere in the Mio-Pliocene, contemporaneous with other changes widely recorded in the Middle East, and in Zagros in particular. This may indicate the real set-up of the zone as a transform zone between the Zagros and Makran, from then on evolving differently (Figure 13b-d). This set-up may be closely related to the change from thin-skinned to thick-skinned tectonics at the same time in the Zagros; meanwhile in Makran tectonics remained unchanged.
- At depth, a north-eastward dipping plane is linked to the Zagros, probably an under-thrusted slice. This plane seems to connect to the Zendan fault at surface.
- An important clue is whether Musandam (Oman) acts as an indenter. Our conclusion is that there is no first-order indentation (Figure 13e). In turn, it could be a second-order indentation explaining the modern Fars Arc curvature (Figure 13f).
- Laboratory experiments and a real analogue help us to imagine the future of such a transform zone: the fault zones are likely to simplify in locating the deformation in a single low-segmented fault. There is no clear evidence at present, however, that the fault zones will coalesce into a single one.

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